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(54) **A system for the acoustic propagation of data along a borehole drilling string.**

(57) A preferred system has a piezoelectric transducer (67*a*) disposed in a bore (64*a*) in a cylinder (63) forming part of a down-well transmitter unit (37). The transducer (67*a*) operates in the relatively low loss acoustic propagation range of the well drilling string (35). The efficiently coupled transmitting transducer (67*a*) incorporates a mass-spring-piezoelectric transmitter combination permitting a resonant operation in the desired low frequency range.

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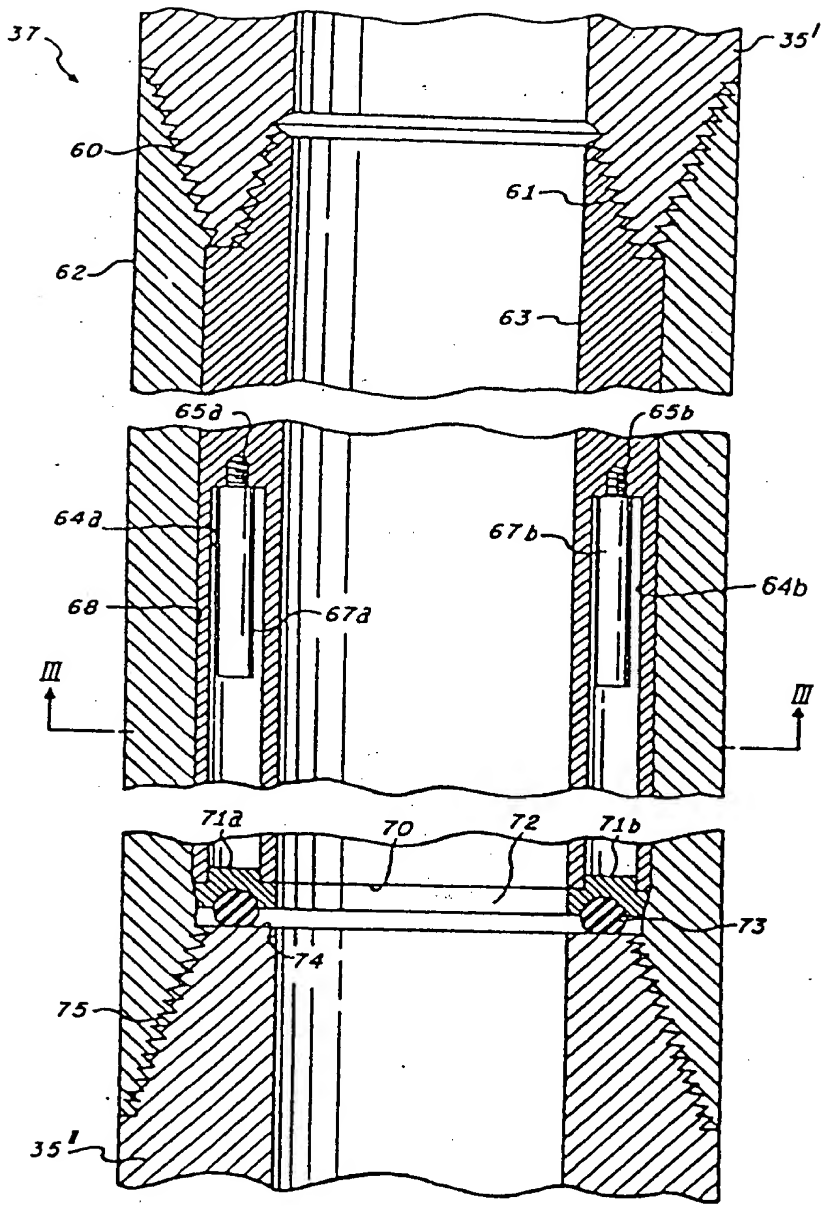
37
35'
60
61
62
63
65a
65b
64a
67b
64b
68
67a
III
III
71a
70
72
71b
73
74
75
35'

FIG. 2.

A system for the acoustic propagation of data along a bore-hole drilling string.

This invention relates to systems for the acoustic propagation of data along bore-hole drilling strings. More particularly, the invention concerns such systems affording improved operation in the relatively low loss acoustic frequency propagation range of the drilling strings.

There are many illustrations in the prior art of data transmission systems for telemetering data in either direction along bore-hole or well drilling strings, some employing electrical and others acoustic propagation. The acoustic systems generally operate in relatively high frequency ranges spaced apart from the large volume of low frequency energy developed by the operating elements of the drilling process. Most of the drilling noise is concentrated in the relatively low frequency range which is desirable for acoustic telemetering because of its relatively low propagation loss characteristics. It is the object of the present invention efficiently to couple acoustic energy into the drill string at relatively high levels competitive with the level of the drilling noise.

According to the present invention there is provided a system for the acoustic propagation of data along a bore-hole drilling string having a longitudinal axis, comprising piezoelectric transmitter means adapted for compression and elongation along a sensitive axis substantially parallel to the longitudinal axis when subjected to a variable electric field representative of the data to be propagated, spring means having one end

thereof connected to the piezoelectric transmitter means, and mass means connected to the other end of the spring means.

The present invention provides, in one preferred form to be described, an acoustic communication system including an acoustic transmitter and receiver, wherein lower frequency acoustic waves, propagating in relatively loss free manner in well drilling string piping, are efficiently coupled to the drill string and propagate at levels competitive with the levels of drilling machinery generated noise energy also present in the drill string. The transmitting transducer permits resonant operation in the desired lower frequency range. The combination features a spring in the general shape of a bellow having spaced corrugations to provide a suitable spring constant in the longitudinal direction. The spring provides an enclosure within which is mounted a cooperating mass.

The invention will now be further described, by way of example, with reference to the accompanying drawings, in which:-

Figure 1 illustrates, in partial cross-section, an elevation system of drilling apparatus employing an acoustic transmitter system according to the present invention,

Figure 1A is a diagram of surface and other equipment used with the system of Figure 1,

Figure 2 is a cross section on a vertical plane of a down-well portion of the system of Figure 1,

Figure 3 is a cross section view taken on line

III-III of Figure 2,

Figure 4 is an enlarged view, partly in cross section, of a transducer of the system of Figures 1 and 2,

Figures 5 and 6 are views similar to that of Figure 4, but showing the transducer of first and second modified constructions, respectively,

Figure 7 is a fragmentary cross-sectional view of a part of a piezoelectric driver of Figure 4, 5 or 6,

Figure 8 is an electrical diagram of apparatus for operating the piezoelectric driver of Figure 4 or 5 showing electrical components and their interconnections,

Figure 9 is a graph useful in explaining the second modified construction,

Figure 10 is an electrical diagram of circuitry for operating the piezoelectric driver of Figure 6, and

Figure 11 is an electrical diagram of circuitry alternative to that of Figure 10.

Figure 1 illustrates the principal elements of the novel telemeter or communication system and of the well drilling apparatus employed for drilling a well bore 36 below the surface 33 of the earth. The drilling apparatus comprises a drill string 35 carrying a drill bit 40 for drilling the bore 36, and the drill string 35 is also simultaneously used as an acoustic propagation medium for telemetering data relative to the progress or state of the drilling operation upward to instruments located above the earth's surface 33.

The drilling apparatus of Figure 1 includes a derrick 18 from which is supported the drill string 35

terminated by the drill bit 40. The drill string 35 is suspended by a movable block 13 from a top platform 10 of the derrick 18 and the vertical position of the drill string may be changed by operation of the usual cable loop 12 by a winch 11 suspended from the platform 10. The entire drill string 35 may be continuously rotated by the rotation of a rotary table 20 and a polygonal kelly 16 slidably passing through a correspondingly shaped aperture in the rotary table 20. A motor 17 located on the surface or drilling platform 22 near the rotary table 20, and a shaft 19 are used to drive the table 20 and therefore to rotate the drill string 35. This conventional apparatus may be completed in essential detail by a swivel injector head 14 at the top of the kelly 16 for receiving drilling mud forced through a pipe 15 by a pump located in mud pump apparatus 21. The drilling mud is forced down into the well through the hollow pipe of the drill string 35 and into the working region of the bit 40 for cooling purposes and for removing debris cut out by the bit 40 from the well bore. The used mud and its included debris are returned upwards to the earth's surface 33 in the bore 36, where conventional apparatus (not shown) separates the mud, rejuvenating it for further cycles of use.

The portion of the drill string 35 below the earth's surface 33 will generally contain many major sections of threaded-together pipe elements. Near the earth's surface 33 and at the lower part of the drill string 35, there will appear sub-units or pipe-like segments of minor length similarly joined in the drill string and sometimes larger

in diameter than the major and much longer elements of the drill string. As has been well established in the art, these sub-units are provided as protective containers for sensors and their ancillary circuits, and for power supplies, such as batteries or conventional mud driven turbines which drive electrical generators or other means to supply electrical energy to operate sensor devices or the like.

As noted, the drill string 35 serves as an acoustic energy propagation path, whereby data may be telemetered between the bit 40 and surface monitoring apparatus. It will be seen that the drill string 35 has three sub-units adjacent the bit 40, by way of example. In ascending order above the drill bit 40, the first of these is the acoustic isolator sub-unit 39 including a mechanical filter for isolating the communication system from the energetic and wide band noise generated by the drill bit 40 during its actual operation. Such mechanical filters are well known in the prior art, as typified by apparatus disclosed in U.S. Patent No. 4,066,995.

In the next sub-unit 38 is installed in a conventional manner a sensor or sensors adapted to generate an electrical measure or measures of data relating to the operation of the drill bit 40, such as fluid pressure or temperature or the like. The sensor output signals are used to modulate an acoustic transmitter located in the third of the series sub-units 37. It will be realised that pluralities of sensors may be served in this manner by employing multiplexing apparatus such as disclosed in U.S. Patent No. 3,988,896. The vibrations of an acoustic

transmitter within the sub-unit 37 are coupled to the drill string 35, thereby exciting a data encoded acoustic wave which propagates towards the earth's surface 33 along the drill string 35. In some applications, several functions may be performed in the same sub-unit, such as the functions performed in sub-units 37 and 38.

Near the top of the drill string 35 is located a conventional receiver sub-unit 32 for containing a device for receiving the acoustic wave propagating within the drill string 35. The receiver within the sub-unit 32 may be made directional and is adapted to furnish the telemetric data via terminals 31 through a band pass electrical filter 50 of Figure 1A to a display such as a conventional electrical meter 51 or to a suitable recorder 52. It will be appreciated by those skilled in the art that a synchronously multiplexed receiver and recorder system such as illustrated in the aforementioned U.S. Patent 3,988,896 may alternatively be employed.

Between the receiver sub-unit 32 and the rotary table 20, there is disposed in the drill string 35 a second noise isolation sub-unit 30 which may contain a mechanical filter generally similar to that of the sub-unit 39. The function of the unit 30 is to attenuate vibrations within the pass band of the receiver due to the gear driven rotation of the rotary turn table 17 and to the operation of various other apparatus on the drilling platform 22, including the kelly 16. Acoustic noise within the pass band of the receiver that may arrive at the receiver input as a result of pulsations in the flowing mud generated by

the mud pump of the apparatus 21 may also be attenuated by placing a suitable damper (not shown) in the pipe 15.

Figures 2 and 3 illustrate in more detail the actual location of the acoustic transmitter within the walls of the acoustic transmitter sub-unit 37. The housing of the sub-unit 37 consists of two cooperating coaxial hollow cylinders 62, 63. The inner cylinder 63 is attached by threads 61 to the lower end of a part 35' of the drill string 35 of Figure 1 and ends at surface 70 at right angles to the axis of the drill string. The outer hollow cylinder 62 has an inner wall 68 which is normally in contiguous relation with the outer surface of the cylinder 63. Furthermore, the outer cylinder 62 is attached by threads 60 to the upper drill string part 35'.

As is seen in Figures 2 and 3, the hollow cylinder 63 is equipped with a plurality of circumferentially spaced and axially extending bores, such as the opposed bores or cylindrical cavities 64<u>a</u>, 64<u>b</u> which may be interconnected. The two opposed bores or cavities 64<u>a</u>, 64<u>b</u> contain active co-phasally driven electric-acoustic transducers 67<u>a</u>, 67<u>b</u> forming the aforementioned transmitters, while other of the bores (shown in Figure 3) may be used as locations for other down-well equipment or for conventional vibration-driven power supplies or batteries for activating those various electronic elements, including apparatus associated with the acoustic transducers.

As mentioned, the opposed bores 64<u>a</u>, 64<u>b</u> contain respective electric-acoustic transducers 67<u>a</u> and 67<u>b</u>. The transducer 67<u>a</u> within the bore 64<u>a</u> includes a piezoelectric

driver 66a (Figure 4) and resonating mass system 90,91,96, both supported in colineal relation by a threaded bolt 86 the upper threads 65a of which extend into a threaded bore 80 at the upper internal end of the bore 64a.

To keep the drilling mud, flowing in interior of the hollow cylinder 63, from entering the bores such as the bore 64a, a ring-shaped end piece 72 is provided fitting against the end 70 of the cylinder 63. The ring 72 is equipped with circumferentially spaced circular bosses (such as bosses 71a, 71b)which extend into the respective bores (such as 64a, 64b), thereby excluding contaminants. The ring 72 may be permanently or semi-permanently affixed to the end 70, as desired. Other closure means may be used.

The outer hollow cylinder 62 is equipped with threads 75 at its lower end to enable the sub-unit 37 to be coupled to the next lowest part 35'' of the drill string 35. In addition, the drill string part 35'' is equipped with a flat upper surface 74 perpendicular to its central longitudinal axis. When the sub-unit 37 is attached to the drill string part 35'', an O-ring 73 or equivalent sealing member is compressed by the surface 74 into an annular O-ring seat disposed in the lower annular face of the ring 72. Alternatively, the O-ring may be dispensed with, the surface 74 engaging the lower planar surface of the ring 72. It will be seen that the assembly permits successful successive coupling and uncoupling of the sub-unit 37 between the drill string parts 35', 35'', the inner cylinder 63 containing and protecting the acoustic

transmitter system and the outer cylinder 62 cooperating in the same function and also serving as the primary load-bearing connection between the drill string parts 35', 35''. It will be understood by those skilled in the art that the Figure 2 transducer 67a and its containing cylinder 63 may be inverted so that the bore 64a points upwardly and so that the transducer 67a projects upwardly from a corresponding bolt having threads 65a. It will further be understood that the dimensions and proportions in the various figures have been distorted in the interests of making the drawings clear and that the proportions illustrated would not necessarily be used in practice. In one practical embodiment of the invention, by way of example, the transducer 67a was about 2.5cm (1 inch) in diameter, its overall length about 45cm (1.5 feet), and the mass-spring resonator was about 60cm (2 feet) long.

The transducers 67a, 67b of Figure 2 each take the form shown in more detail in Figure 4; as shown in Figures 2 and 4, each such transducer is suspended by the headless bolt 86, the upper threads 65a of which are threaded into the bore 80 within the top surface of a wall of the hollow cylinder 63. The bolt 86 extends through the generally conventional sonic piezoelectric wave exciter or driver 66a including, as will be further discussed, an assembly of piezoelectric discs. The piezoelectric discs of the driver 66a are maintained in axial compression between apertured insulator end discs 81, 84. This is accomplished by the hollow cylindrical portion 85 of a cooperating steel member having an axial

bore 88, the bore 88 being threaded on the lower end of the bolt 86. In practice, the hollow internally threaded part 85 is rotated on the threads of the bolt 86 until the stack of ceramic high dielectric discs within the piezoelectric driver 66a experiences the desired level of compression. The threaded steel part 85 may then be fixed against further rotation with respect to the threads of the bolt 86 in any convenient manner. If desired, the upper threads 65a of the headless bolt 86 may be pinned in the same manner, but with respect to the wall of the cylinder 63. The bolt 86 is made of age-hardened, high strength, low thermal expansion alloy such as a corrosion resistant alloy of nickel, iron, and chromium sold as type 903 under the trademark Incoloy by the International Nickel Company of U.S.A. In any event, when the bolt 86 is once properly stressed by rotation of the threaded steel part 85, compression of the stack of piezoelectric elements of the driver 66a remains substantially constant.

The threaded steel part 85 forms a suspension for a spring-mass system which is vibrated vertically (i.e. longitudinally) by the piezoelectric driver 66a. A hollow tube 87 has an end section 87a whose inner diameter matches the outer diameter of the part 85 and is welded or otherwise permanently affixed thereto. At a mid-section of the tube 87 is a bellows-like corrugated section 89 which forms an active axial spring for the system. The spring bellows 89 and its opposite constant diameter ends 87a,87b are preferably formed of a stainless steel tubing with its mid-section 89 swaged into a regular multiply corrugated shape

for providing the required longitudinal spring action along the spring axis. Characteristic of the spring section 89 is the fact that it desirably retains substantially the same lateral rigidity as is present in the original tube itself.

At the end 87b of the tube 87, the inner diameter of the tube section matches the outer diameter of a section 90 of the suspended mass system 90, 91, 96 and is fastened permanently thereto, as by welding. A tapered portion 95 integral with the section 90 extends above it and integrally supports a mass element 96 whose diameter is designed to clear the inner surface of the bellows spring 89. The lower end portion 91 of the mass system 90, 91, 96 has an expanded diameter relative to portions 90, 96, but slidably clears the inner surface of the bore 64a in the cylinder 63. Affixed in a ring-shaped depression in the mass part 91 is an annular bearing 92 constructed of hardened steel, lubricated upon assembly. The bearing surface provided moves axially in relatively friction-free manner in contact with the steel surface of the circular bore 64a. Another annular bearing 94 is permanently affixed to the inner wall of the unconvoluted end 87a of the tube 87 so that the free end of the mass 96 may slide easily therewithin and so that the mass 96 does not contact the bellows spring 89. Bearings 92 and 94 are preferably of hardened steel.

The end portion 91 of the mass system is conveniently fitted with an integral hexagonal bolt head 93 to facilitate inserting and withdrawing the assembly from the

threaded bore 80. The integrated mass system 90, 91, 96 may be constructed of steel, though other materials may be found suitable. Sintered or solid tungsten, because of its high density, is specially suitable. Certain known tungsten-copper alloys are also possible materials. An additional advantage of the configuration shown in Figure 4 lies in the re-entrant disposal of the mass elements 90, 91, 95, 96 into the interior of the bellows spring portion 89, making full use of available space and making it possible for the length of the transmitter and of the bores 64a, 64b, to be shortened, thus decreasing the overall length of the sub-unit 37 and its cost.

As shown in Figure 7, a generally conventional piezoelectric driver system may be employed as the sonic driver 66a to produce axial vibrations when an alternating voltage is coupled to leads 82, 83 of Figure 4. In general, the discs making up the driver 66a are prepared and assembled following prior art practice such as widely discussed in the literature. In one design of the driver 66a, a stack of about 200 ceramic apertured discs such as disc 123 is employed, each disc having a 2.2cm ($\frac{7}{8}$ inch) outside diameter and a centred 1cm ($\frac{3}{8}$ inch) hole. The discs are formed of PZT 5550 material readily available commercially. The opposed faces of each disc 123 are optically lapped and supplied with a sputtered chromium layer such as layers 122, 124 adhered to the ceramic surface and then an electrically conductive gold layer such as layers 121, 125 readily adhesive to the chromium. When the discs are stacked, thin conductive plates, such as the

apertured plates 120, 126 are interposed. Alternate ones of these plates, such as plate 126, are coupled to one terminal of the a.c. driving power source by a tab 127, while the intervening plates, such as plates 120, 130, are similarly coupled to the second terminal of that driving power source. The total stack of the ceramic discs 123 is electrically in parallel when driven, but yields serial or axial cyclic longitudinal expansion and contraction. A conventional insulating or protective tape may be wrapped around the bolt 86, as at 128, and around the driver stack, as at 129.

In Figure 8, a power supply and control suitable for driving two of the transducer drivers 66<u>a</u>, 66<u>b</u> of Figure 4 are shown, the two drivers being connected in parallel and then in series through an electrically resonating inductance 100 to the output of a power amplifier 101. The amplifier 101 may be driven by a conventional tunable oscillator 102 operating in the general region of 400 Hz., for example.

The oscillator 102 may be put into action by a time programmed switch 104 which may be controlled through a mechanical link 105 by a conventional programmer 106 operated by a clock 108 via a mechanical link 107. In this manner, economical use may be made of a d.c. supply or battery 103, since the transducer system needs to be operated periodically for only a fraction of a minute in order to convey sufficient data to the earth's surface. Furthermore, the arrangement makes it easy to start the clock 108 as the sub-unit 37 is inserted at the earth's

surface into the drill string 35 to be lowered into the well.

It will also be understood that data sensed by a sensor such as a pressure pick-off 109 may be coded by well known means and supplied as an intelligence bearing modulation by a modulator 112 to the carrier frequency generated by the oscillator 102 in the general manner taught, for instance, in the aforementioned U.S. Patent No. 3,988,896. Additional pick-offs or sensors 110, 111 may be used in a similar manner to convey data to the earth's surface for display or recording purposes employing the concepts of U.S. Patent No. 3,988,896 for synchronous multiplexing and demultiplexing of the data. The sensors 109, 110, 111 may provide information on pressure, temperature, or other variables.

It will be seen that, for greatest energy transfer between the amplifier 101 and the drill string 35, the transducer should be adjusted to be mechanically and electrically resonant at the same frequency. The piezoelectric driver 66a is electrically capacitive (C) so that inductor 100 (L) is made adjustable to the appropriate value, giving a resonance frequency F_1:

$$F_1 = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

Where two transducers are in parallel, the value C will, of course, be the effective capacitance of the parallel connected transducers. The series inductance 100 has the effect of amplifying the voltage across the drivers 66a, 66b in proportion to the quality factor Q of the circuit. The electrical resonance is complemented by the mechanical

resonance across each piezoelectric driver 66a, 66b. The mechanical loading of the piezoelectric stack with the stiff spring 89 and the extended mass makes use of the stack compliance and the spring compliance to aid in controlling the free vibration of the mass. The mechanical resonance frequency F_2 for a mass of M kilograms and a proportionality constant K in Newtons per metre is readily calculated as:

$$F_2 = \frac{1}{2} \sqrt{\frac{K}{M + \frac{m}{3}}}$$

Since the spring 89 contributes about one third of its mass m to the inertia of the moving system, this contribution must be accounted for in the equation for F_2.

It is seen that the mass-spring combination permits resonant operation of the piezoelectric transducer and is a useful means for extending the mechanical resonance of the piezoelectric system to lower frequencies than is conventionally possible. The selected resonant frequency may be lower than previously, in the frequency range within which acoustic transmission losses in the drill string are favourably lowest. Those skilled in the art will appreciate that the transducer will serve as an acoustic receiving transducer equally as well as a transmitter of acoustic waves.

Figure 5 shows a first modified construction of the transducer 67a, parts similar to those of Figure 4 being given the same reference numerals. As in Figure 4, each transducer 67a of Figure 5 is suspended by a headless bolt 86 having upper threads 85 threaded into a bore 80 within the top surface of the wall of the hollow cylinder 63.

The bolt 86 extends through the conventional wave exciter or driver 66a of the form shown in Figure 7. The bolt 86 is threaded in a bore 88 of a cooperating steel part 85. The threaded steel part 85 is secured against rotation with respect to the threads of the bolt 86 by the insertion of a taper pin 87 in a conventional manner. If desired, the upper end of the headless bolt 86 may be pinned in the same manner, but with respect to the wall of the cylinder 63.

The bore 88 continues into the start of an extended steel rod 187 which forms a major part of a vibratable mass. Before ending in the principal mass 180, the bore 88 cooperates in forming a stiff helical spring 189 with a generally rectangular cross section, formed by using any suitable machining process to cut away metal between turns from the start of the helix at 190 to its end at 191 all of the way into the bore 88. The steel spring 89 and the mass of the steel rod 187 cooperate in defining the resonance characteristics of a mechanical vibratory system which is to cooperate with an electrically resonant system employing the effective capacitance of the piezoelectric array and a cooperating series inductor shown generally at 100 in Figure 8.

The vibratory system is supported at the top of bolt 86 and is further restricted so that its axis remains coincident with the axis of the bore 64a. This latter is accomplished by the use of three hardened steel bearings 195a, 195b, and 195c having lubricated bearing surfaces extending radially at the lower end of the rod

mass 180. Equally spaced about the circular cylindrical surface of the rod 187, their bearing surfaces move in relatively friction free fashion in contact with the steel surface 198 of the circular bore 64a. The lower end 196 ·. the steel bar mass 180 is conveniently cut to form a hexagonal bolt head 197 to facilitate inserting and withdrawing the assembly from the bore 80. The part 85, the helical spring 189, and the mass 180 may be made of high quality spring steel, although other materials may be found suitable. Solid or sintered tungsten, because of its high density, is also of interest, and alloys of tungsten compounded with copper.

In the modified construction of Figure 6, the annular bearing 94 of Figure 4 is omitted, but the lower end of the mass 91 is equipped with a conventional accelerometer 294 whose output leads appear at 295. The generally conventional piezoelectric driver 66a of Figure 6 is as shown in Figure 7.

In the modification of Figure 10, the accelerometer 294 of Figure 6 is again shown mechanically affixed directly to the driving transmitter of the transducer 67a. The output of the accelerometer 294 is coupled via lead 301 to junction 299 of an input biasing network including the grounded bias resistor 300 and then into a preamplifier 302 supplied in the usual manner via power input terminals 303, 304. The second cooperating terminal of preamplifier 202 is coupled in the feedback network at junction 308 wherein capacitor 307 and resistor 306 are series coupled to ground and through the parallel disposed

capacitor 305 and resistor 309 coupled to junction 310. The circuit associated with the preamplifier 302 serves as a high impedance buffer stage and provides gain control.

The preamplifier output is fed from the junction 310 through the signal terminals of field effect transistor 325 to one input terminal of amplifier 332, the other input 311 of which is grounded. Amplifier 332 is supplied with the usual power input terminals 330, 331 and with a variable feedback network including capacitors 327,333 and variable resistor 328, and provides a useful output at terminal 332a. Amplifier 332, together with the series coupled preamplifiers 340 and 361 cooperate to limit the band width of the signal. Amplifier 340, whose input at 335 is provided through junction 332a and resistor 334, is provided with power at terminals 337, 338, has a feedback capacitor 339, a feedback resistor 336, and an output coupled through variable resistor 356 to an input of amplifier 361. Amplifier 361 has feedback capacitors 357 and 360, together with the usual power inputs 359 and 362. Its output on lead 363 and terminal 358 is fed back through variable resistor 354 and lead 326 to the input terminal 329 of the aforementioned amplifier 332. Variable resistors 354, 356 are gang coupled by linkage 355. Amplifier 332 is coupled as an integrator, amplifier 340 as an inverter, and amplifier 361 as a second integrator so that a differentiated form of the input at 329 appears on feedback lead 326. Control of network 327, 328 determines the gain-band width of the active filter assembly of amplifiers, while the adjustable resistors 354, 356 set

the centre frequency of the effective filter pass band. This pass band encompasses the mechanical resonance peaks of the transmitter of transducer 67a, together with the maximum anticipated drift from that centre frequency.

The useful output of amplifier 332 at terminal 332a is coupled via lead 404 and resistor 405 to one input 432 of power amplifier 435 having the usual supply terminals 433, 436 and a feedback capacitor 434 and resistor 430. The second input to power amplifier 435 is coupled through resistor 411 to ground. The amplified power output at terminal 431 is coupled via lead 364 to operate the transmitter of the transducer 67a.

Secondly, the useful output of amplifier 332 at terminal 332a is coupled through resistor 402 and blocking capacitor 403 to a terminal 406 which is the input to a rectifier circuit. The latter includes diodes 401, 407 poled as shown, with a cooperating filter including capacitor 400 and resistor 390. The output of the rectifier on lead 388 passes into one terminal of direct current amplifier 383 having a feedback capacitor 382 and biasing resistor 384. Amplifier 383 acts as an active gain-limiting element in an automatic gain control circuit and is supplied with power via terminals 386, 387. Its output at junction 385 is fed through blocking diode 381 to junction 380 for supply through resistor 379 to ground and through resistor 378 via lead 377 to the current control biasing gate electrode of field effect transistor 325. The second input of d.c. amplifier 383 is supplied with a bias signal by virtue of potentiometer 410, lead

437, capacitor 408, and a power source (not shown) coupled to terminal 409 of potentiometer 410.

Thus, the automatic gain control loop is completed; the system will oscillate at a frequency at which the loop gain is unity and phase shift is zero. If the loop gain is greater than unity, the amplitude of oscillation automatically increases until some element in the loop shows non-linear behaviour. To avoid consequent generation of a non-linear waveform, the automatic gain control circuit adjusts the gain to produce a constant amplitude purely sinusoidal output.

The network found in Figure 10 between junction 310 and the bias gate electrode of the gain controlling field effect transistor 325 acts as a distortion minimizing network, changing the bias on the field effect transistor gate electrode as the waveform goes below the zero level. It includes a voltage divider comprising resistor 370, variable resistor 375, and capacitor 376, the centre tap 371 between resistors 370, 375 being coupled through a clipper diode 372 to the tap 374a of a potentiometer 374. A bias is supplied through tap 374a by coupling potentiometer 374 between ground and resistor 373, one terminal 369 of which is coupled to a negative voltage source (not shown).

In the modification disclosed in Figure 11, quick starting is enhanced and non-linearity of operation is avoided by the use of a phase-locked loop. The circuit runs freely in an open loop sense in starting, and then locks at its steady state operating frequency, the frequency that generates the correct phase shift through

the mechanical portions of the system.

In Figure 11, the accelerometer 294 is again shown mechanically affixed directly to the driving transmitter of the transducer 67<u>a</u>. The output of the accelerometer 294 is coupled via lead 460 across input resistor 461 to one input of an amplifier 463 having the usual power supply inputs 462, 464. The second cooperating terminal of preamplifier 463 is coupled in a feedback network at junction 459 wherein capacitor 465 is coupled through the variable gain controlling resistor 466 to ground. To complete the feedback path, the output terminal 468 of amplifier 463 is coupled through resistor 467 to input junction 459.

The output of amplifier 463 may be corrected for phase compensation purposes before lowering the equipment into the well by the manual positioning of switch 469 so as to select an appropriate one of two inputs to the conventional phase detector 478. The signal at junction 468 may be injected into detector 478 through an R-C path (provided by a capacitor 470 and a resistor 472) or through a second R-C path (provided by a capacitor 471 and a resistor 473) having distinctive parameters. The input signal is compared in phase detector 478 to a fed back signal on lead 279.

The output of phase detector 478 is a bipolar direct current signal used to control the frequency of a conventional current-controlled oscillator 506 which operates in locked-oscillator fashion to supply alternating power via terminal 511 to drive the transducer 67<u>a</u>. The

bipolar direct current is filtered by R-C network provided by resistor 480 and capacitor 481 and is applied via input resistor 505 to the control terminal of oscillator 506. The adjustable resistor network 507 is a conventional part of oscillator 510 and is provided for the purpose of setting the free running frequency within the locking range of the phase-locked loop. The adjustable resistor 507 operates in conjunction with capacitor 508 for this purpose.

In operation, the output terminal 511 of oscillator 506 is supplied with a positive potential through resistor 509 from a power supply (not shown) at terminal 513. Terminal 511 is coupled via lead 512 to one input of amplifier 500, supplied with power input terminals 489,490. The output terminal 485 of power amplifier 500 is coupled to the input of the transmitter of the transducer 67<u>a</u>. It is also connected to ground through resistors 486, 487 having a common junction 488, which terminal 488 is coupled back to the second input terminal of power amplifier 500.

It is seen that the mass-spring combination of Figure 6 and Figure 10 or 11 permits self-resonant operation of the piezoelectric transducer, as well as having the advantages enumerated for the previous embodiments.

CLAIMS

1. A system for the acoustic propagation of data along a bore-hole drilling string having a longitudinal axis, characterised by piezoelectric transmitter means (66a,66b) adapted for compression and elongation along a sensitive axis substantially parallel to the longitudinal axis when subjected to a variable electric field representative of the data to be propagated, spring means (89; 189) having one end thereof connected to the piezoelectric transmitter means (66a,66b), and mass means (90,91,96; 180) connected to the other end of the spring means (89; 189).

2. A system according to claim 1, characterised in that the piezoelectric transmitter means (66a, 66b) form part of an acoustic transducer (67a,67b) physically coupled to the bore-hole drilling string (35), the acoustic transducer additionally comprising first fastener means (86) extending through said piezoelectric transmitter means (66a,66b) along said sensitive axis, and second fastener means (85) for affixing said piezoelectric transmitter means (66a,66b) against a surface of said bore-hole drilling string (35) and for holding said piezoelectric transmitter means (66a,66b) in cooperation with said first fastener means (86) in substantially fixed compression, and wherein the spring means are constituted by corrugated tubular bellows-like spring means (89) affixed to and extending from said second fastener means (85) opposite said piezoelectric transmitter means and having an axis colineal with said sensitive axis, and the mass means are constituted

by elongate cylindrical mass means (90,91,96) having a cylinder axis colinear with said sensitive axis and extending from and coupled integrally with said corrugated tubular bellows-like spring means (89) into the interior thereof opposite said second fastener means.

3. A system according to Claim 2, characterised in that said piezoelectric transmitter means (66a,66b) and said corrugated tubular bellows-like spring means (89) are characterised by supporting mechanical resonance with respect to said elongate cylindrical mass means (90,91,96) at a predetermined frequency.

4. A system according to Claim 3 and characterised by further including electrical signal generator means (102,112), and inductive means (100) coupled in series relation between said electric signal generator means (102,112) and said piezoelectric transmitter means (66a,66b), said inductive means(100) and said piezoelectric transmitter means (66a,66b) being adapted to operate in electrical resonance at said predetermined frequency.

5. A system according to Claim 4, characterised in that said electrical signal generator means (102,112) comprises carrier generator means, sensor means for providing an output characteristic of a measure of a phenomenon existing in the vicinity of said bore-hole drilling string, and circuit means for modulating said carrier as a function of said sensor means output.

6. A system according to any of claims 2 to 5, characterised in that said bore-hole drilling string (35) comprises hollow pipe means having a cylindrical wall (63)

of finite thickness, said cylindrical wall (63) includes at least one cylindrical cavity (64a,64b) disposed entirely within said cylindrical wall, thereby providing said surface of said bore-hole drilling string cooperating with said second fastener means.

7. A system according to Claim 6, characterised in that said cylindrical cavity (64a,64b) additionally includes a cylindrical wall, and said elongate cylindrical mass means (90,91,96) is provided with first substantially friction-free bearing means (92) at its end remote from said second fastener means bearing against said cylindrical wall (64a) for ensuring that the axis of said cylindrical cavity and of said elongate cylindrical mass means (90,91,96) are substantially colineal, said elongate cylindrical mass means being enveloped in major part within said corrugated tubular bellows-like spring means (89).

8. A system according to Claim 7, characterised in that said cylindrical mass means (90,91,96) is additionally provided with second substantially friction free bearing means (94) at its end adjacent said second fastener means bearing against the inner surface of a non-convoluted portion (87a) of said bellows-like spring means adjacent said second fastener means.

9. A system according to any of Claims 1 to 6, characterised in that the piezoelectric transmitter means form part of an acoustic transducer (67a,67b) physically coupled to the bore-hole drilling string (35), the acoustic transducer additionally comprising first fastener means (86) extending through said piezoelectric transmitter means

along said sensitive axis, and second fastener means (85) for affixing said piezoelectric transmitter means against a surface of said bore-hole drilling string (35) and for holding said piezoelectric transmitter means in cooperation with said first fastener means in substantially fixed compression, and wherein the spring means (189) have a compression axis colinear with said sensitive axis and extend from and are coupled integrally with said second fastener means (85), and the mass means are constituted by elongate cylindrical mass means (180) having a cylinder axis colinear with said sensitive axis and extending from and coupled integrally with said spring means (189) opposite said second fastener means (85).

10. A system according to Claims 5 and 9, characterised by further including control means (106,107,108) for intermittent energy-saving operation of said electrical signal generator means (102,112).

11. A system according to Claims 6 and 9, characterised in that said cylindrical cavity (64a,64b) additionally includes a cylindrical wall, and said elongate cylindrical mass means (180) is provided with substantially friction-free bearing means (195a,195b,195c) at its end remote from said spring means (189) and bearing against said cylindrical wall (64a) for ensuring that the axis of said cylindrical cavity and of said elongate cylindrical mass means (180) are substantially coaxial.

12. A system according to Claim 1 for the acoustic propagation of a data bearing carrier signal along a bore-hole drilling string including coupled hollow pipe sections,

characterised by at least one of said hollow pipe sections being aligned along said longitudinal axis and having a closed cavity (64a,64b) in the wall thereof, said closed cavity being aligned along said sensitive axis which is parallel to and offset from said longitudinal axis, said piezoelectric transmitter means (66a,66b) being subjected to the electric field parallel to said sensitive axis, and said piezoelectric transmitter means being affixed to a surface of said closed cavity, wherein the spring means are cylindrical spring means (89) affixed to said piezoelectric transmitter means (66a,66b) opposite said surface, and the mass means are elongate mass means (90,91,96) having an axis collinear with said second axis and affixed to said cylindrical spring means (89) opposite said piezoelectric transmitter means, the system additionally comprising accelerometer means (294) fixedly coupled to said elongate mass means (90,91,96), and amplifier means (303;463) responsive to said accelerometer means (294) for driving said piezoelectric transmitter means.

13. A system according to Claim 12, characterised in that the amplifier means includes preamplifier means (303) responsive to said accelerometer means (294), band width limiting amplifier means (332,340,361) responsive to said preamplifier means (303), feedback means (354,326) for coupling the output of said band width limiting amplifier means to an input thereof, and power amplifier means (435) responsive to said band width limiting amplifier means for driving said piezoelectric transmitter means.

14. A system according to Claim 13 and characterised

by further including gain control means (383) responsive to said band width limiting amplifier means and disposed between said preamplifier means and said band width limiting amplifier means.

15. A system according to Claim 14, characterised in that said band width limiting amplifier means includes in series relation first integrating amplifier means, inverting amplifier means, and second integrating amplifier means.

16. A system according to Claim 15, characterised in that said gain control means includes rectifier means (401,407) responsive to said first integrating amplifier means, fourth amplifier means (383) responsive to said rectifier means, and field effect transmitter means (325) disposed between said preamplifier means and said first integrator means and responsive to said fourth amplifier means.

17. A system according to Claim 12, characterised in that said amplifier means includes preamplifier means (463) responsive to said accelerometer means (294), phase detector means (478) having first and second inputs, said first input being responsive to said preamplifier means (463), and current controlled oscillator means (506) responsive to said phase detector means (478), said phase detector means (478) being additionally responsive to said current controlled oscillator means (506), and said piezoelectric transmitter means (66a) being responsive to said current controlled oscillator means (506).

18. A system according to Claim 17 and characterised

While the invention is particularly suited for use with well drilling equipment and is therefore illustrated herein in such an environment, it has application also in permanent down-well installations, such as in oil or water pumping equipment. In particular, it also has application in the telemetering of data to the earth's surface relative to the performance of a down-well pumping system for extracting energy from hot geothermal brine disposed in subterranean strata of the earth. For example, it finds use in the acoustic data transmitting channel of geothermal systems such as are taught in the aforementioned U.S. Patent Nos. 3,988,896 and 4,107,987.

In the drilling instrumentation, for example, it is required efficiently to drive an acoustic transmitter that is mechanically coupled to the drill string itself, as at sub-unit 37 of Figure 1. Operation of the electrically excitable transmitter generates acoustic waves that propagate upwards in the drill string to the surface-located receiver. Acoustic loss measurements made upon the types of pipes used in well drilling and in geothermal brine pumping systems clearly indicate that the sonic carrier must have a relatively low audio carrier frequency. The relatively low frequencies are required since higher frequencies suffer serious attenuation per unit length of piping of the aforementioned kind and acoustic propagation becomes difficult even at moderate well depths.

A further difficulty lies in the presence in the mechanical structure of the acoustic wave propagating piping of a plurality of sharp resonances whose locations and separations are often difficult to predetermine or to locate empirically in a complex mechanical structure. To achieve reliable and efficient coupling between the acoustic transmitter and the drill string, it is necessary to operate the acoustic transmitter at one of the drill string piping resonant frequencies. As an example, curve 255 of Figure 9

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0033192

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CABLES: SPERIGYCO BRACKNELL

Our Ref: Euro. 4979/80/81

25th March 1981

Receiving Section
European Patent Office
Postbus 5818
2280 HV Rijswijk ZH
Netherlands.

Dear Sirs,

European Patent Application No. 81.300068.4
Correction under Rule 88.

It is hereby requested that a mistake in the above application be corrected under Rule 88 (as interpreted in paragraph 4 of the Reasons for the Decision in Decision of 18 July 1980 J08/80) by introducing the attached insert A (two pages) between lines 12 and 13 on page 17 of the specification.

Insert A represents the passage spanning page 5, line 31 to page 7, line 28 of the specification of U.S. Patent Application No. 114,040 from which priority is claimed and a certified copy of which was filed with the initial papers of the present application. The passage forming Insert A was inadvertently omitted from the specification at the typing stage, the full facts of the matter being set out in the enclosed Statutory Declaration made by the writer.

It is submitted that a case is established that it was the Applicants' intention to include the omitted passage by way of their instructions to combine the disclosures of the three basic U.S. patent applications and that, in any event, the matter in question was disclosed to the European Patent Office at the time of filing the present application by way of the Certified Copy of U.S. Patent Specification No. 114040.

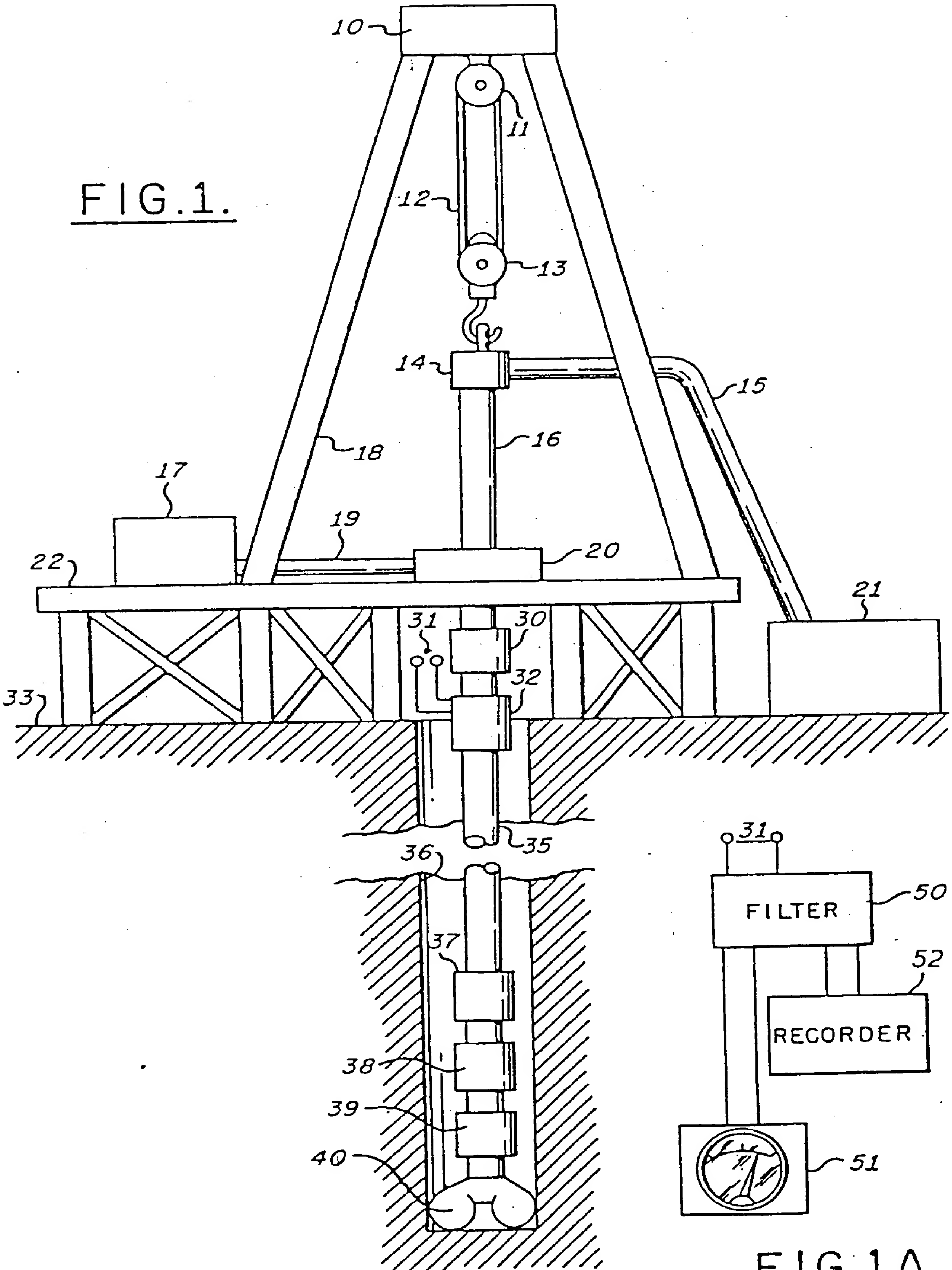
The necessary fee for the requested correction is being remitted separately.

Yours faithfully,

J. Singleton
Authorised Representative

The corrections are allowed
Receiving Section
The Hague 02 06 1981

FIG.1.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RECORDER
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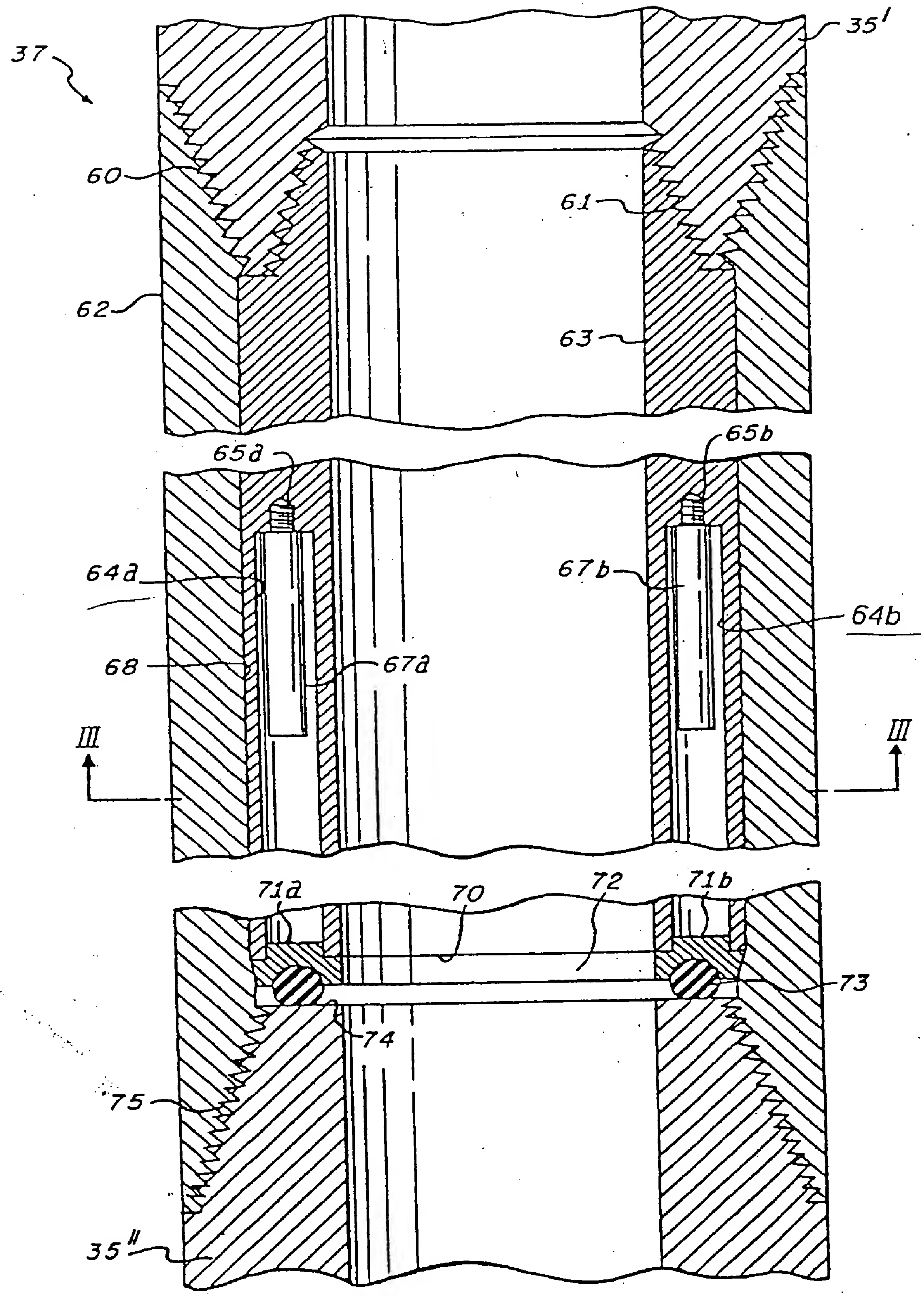
FIG.1A.


37
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62
63
65a
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64a
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68
67a
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72
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75
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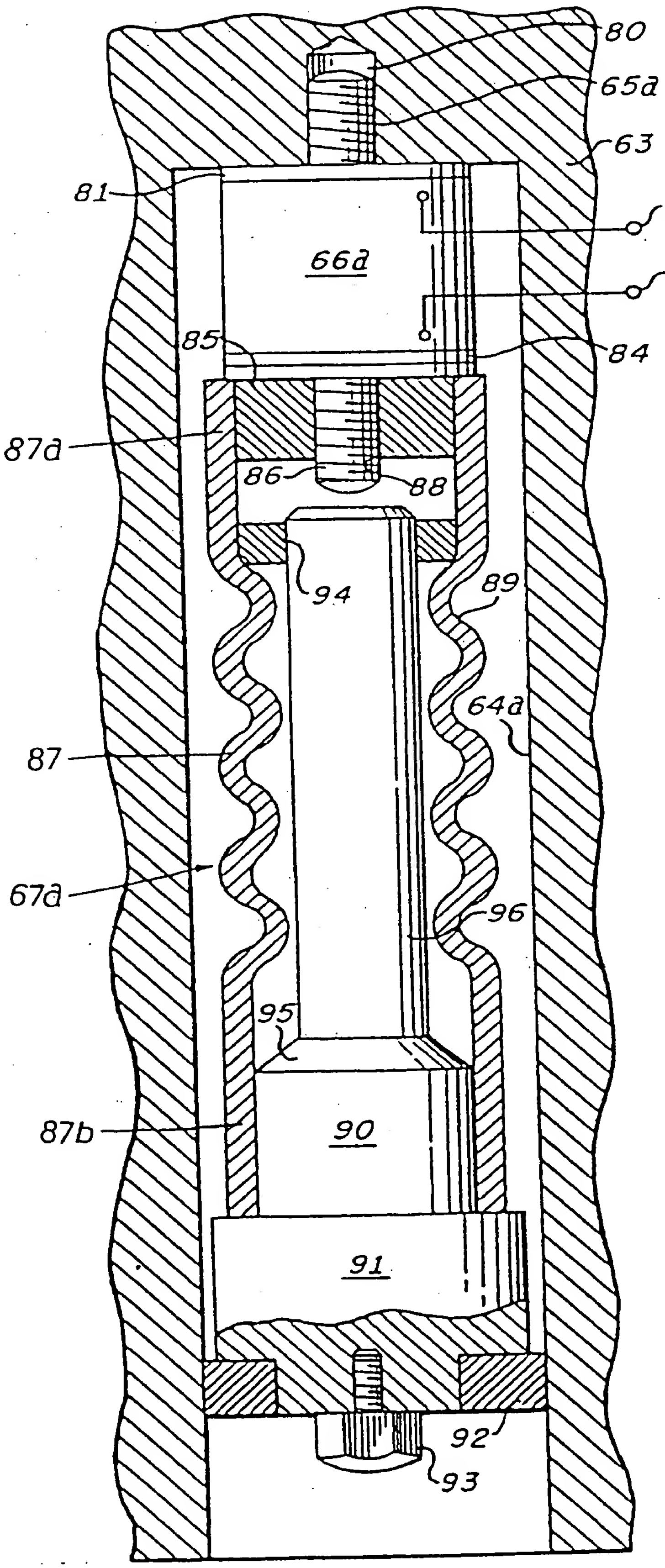
FIG. 2.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66a
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87a
86
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94
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67a
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95
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87b
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93

FIG. 4.

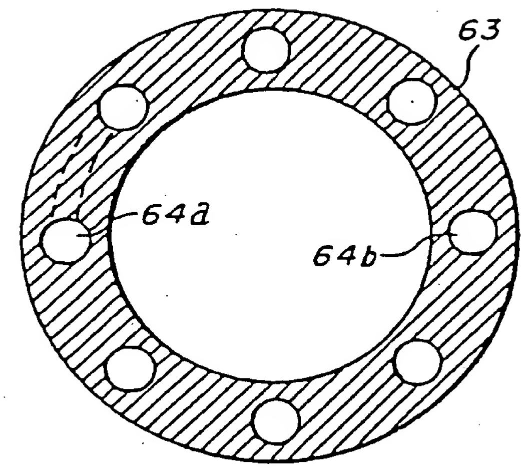
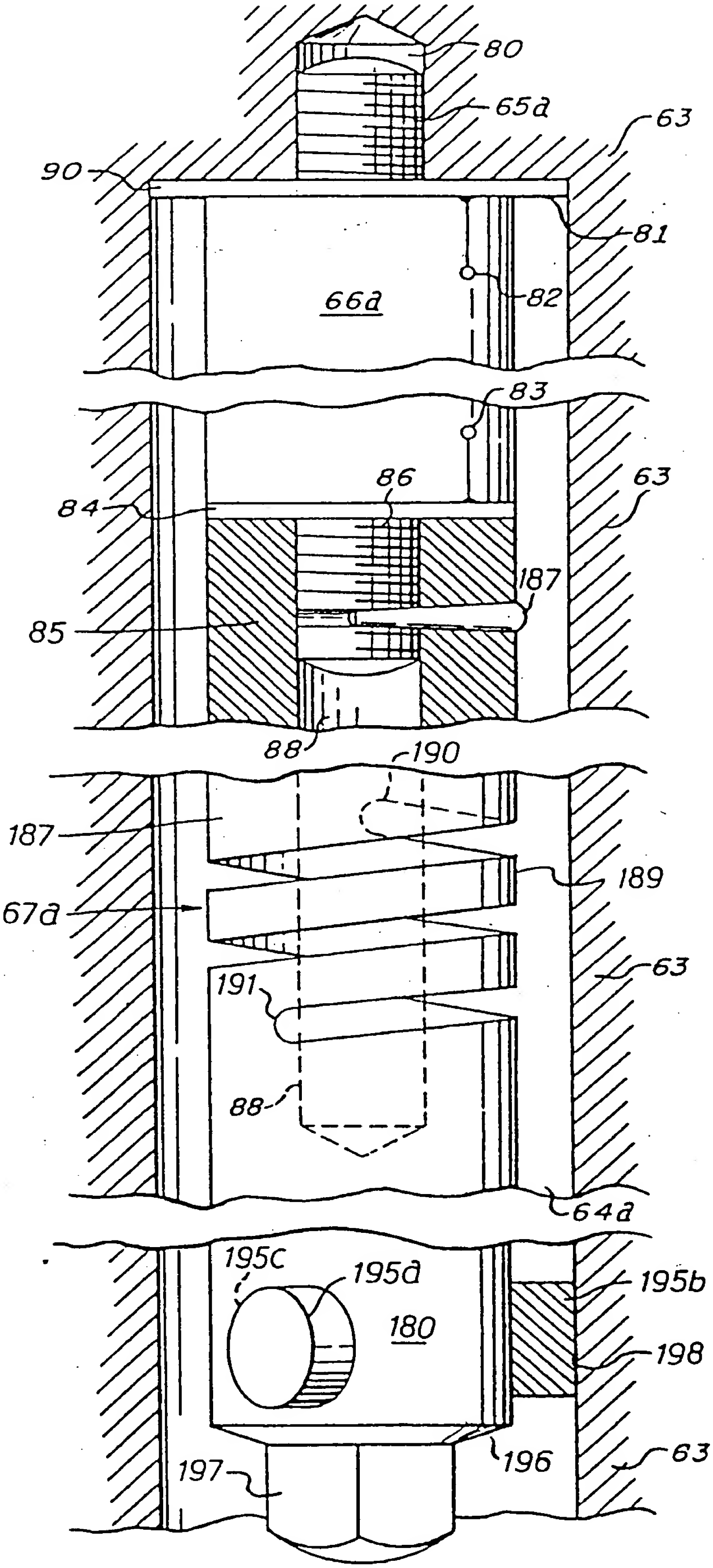

63
64a
64b

FIG. 3.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67a
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191
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64a
195c
195a
195b
180
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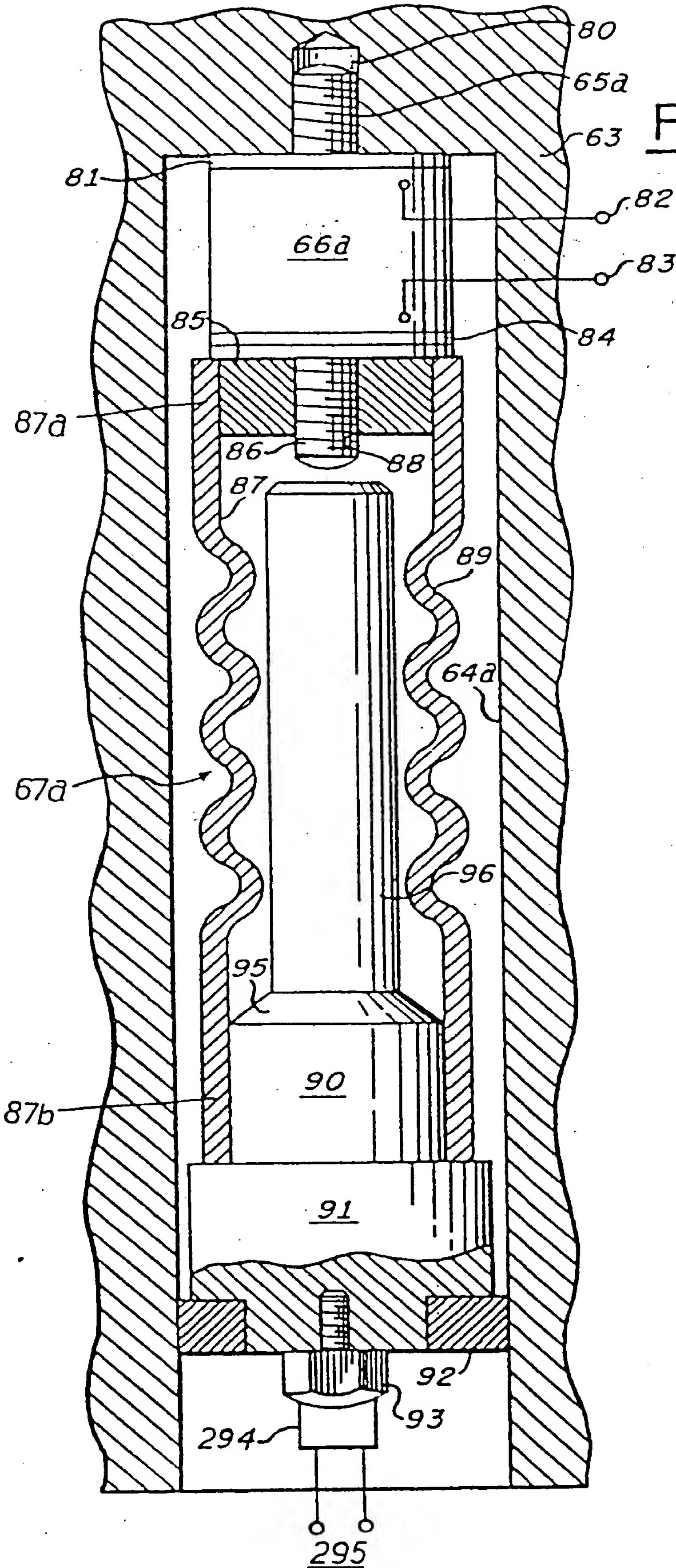
197
63

FIG.5.

FIG. 6.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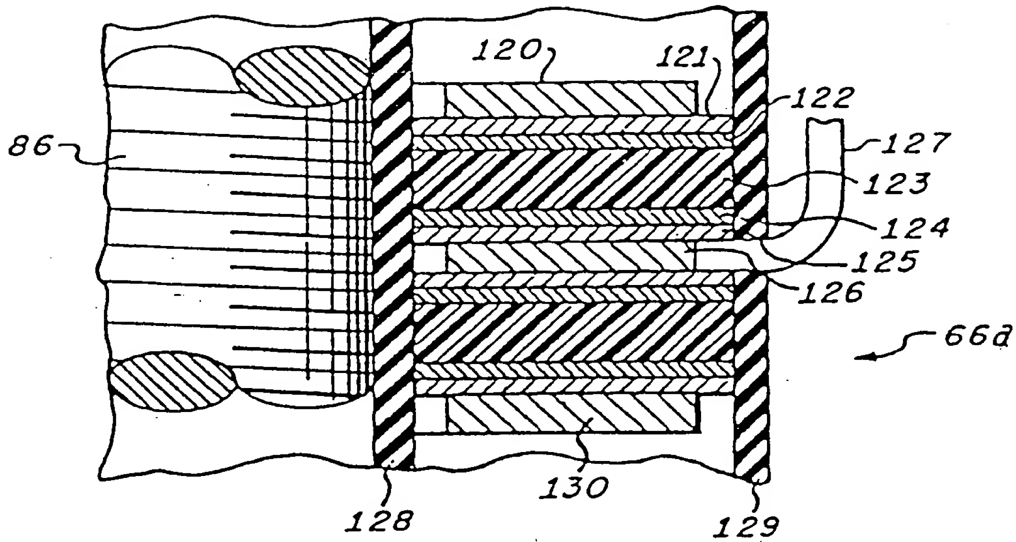
120
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126
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66a
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FIG. 7.

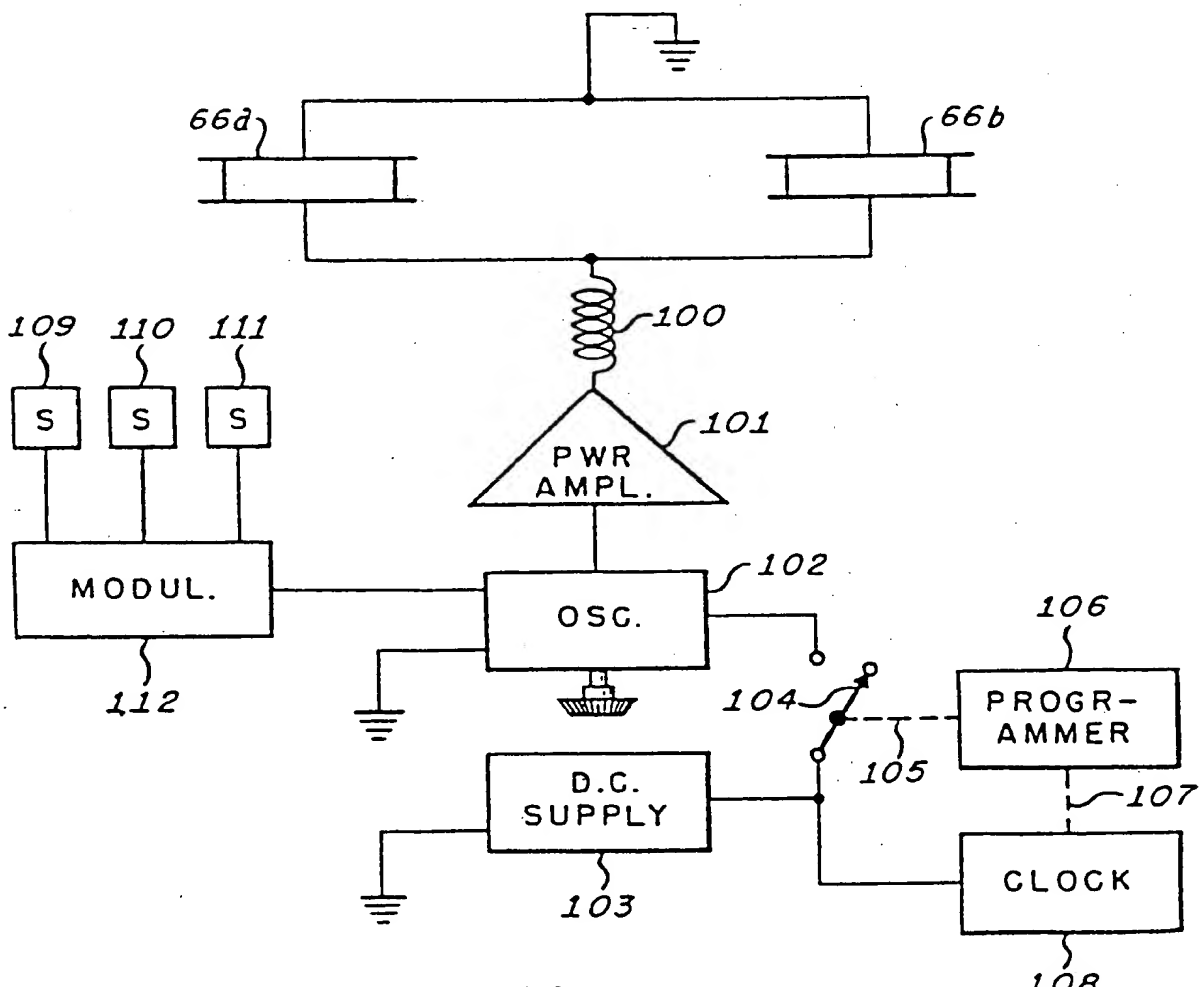
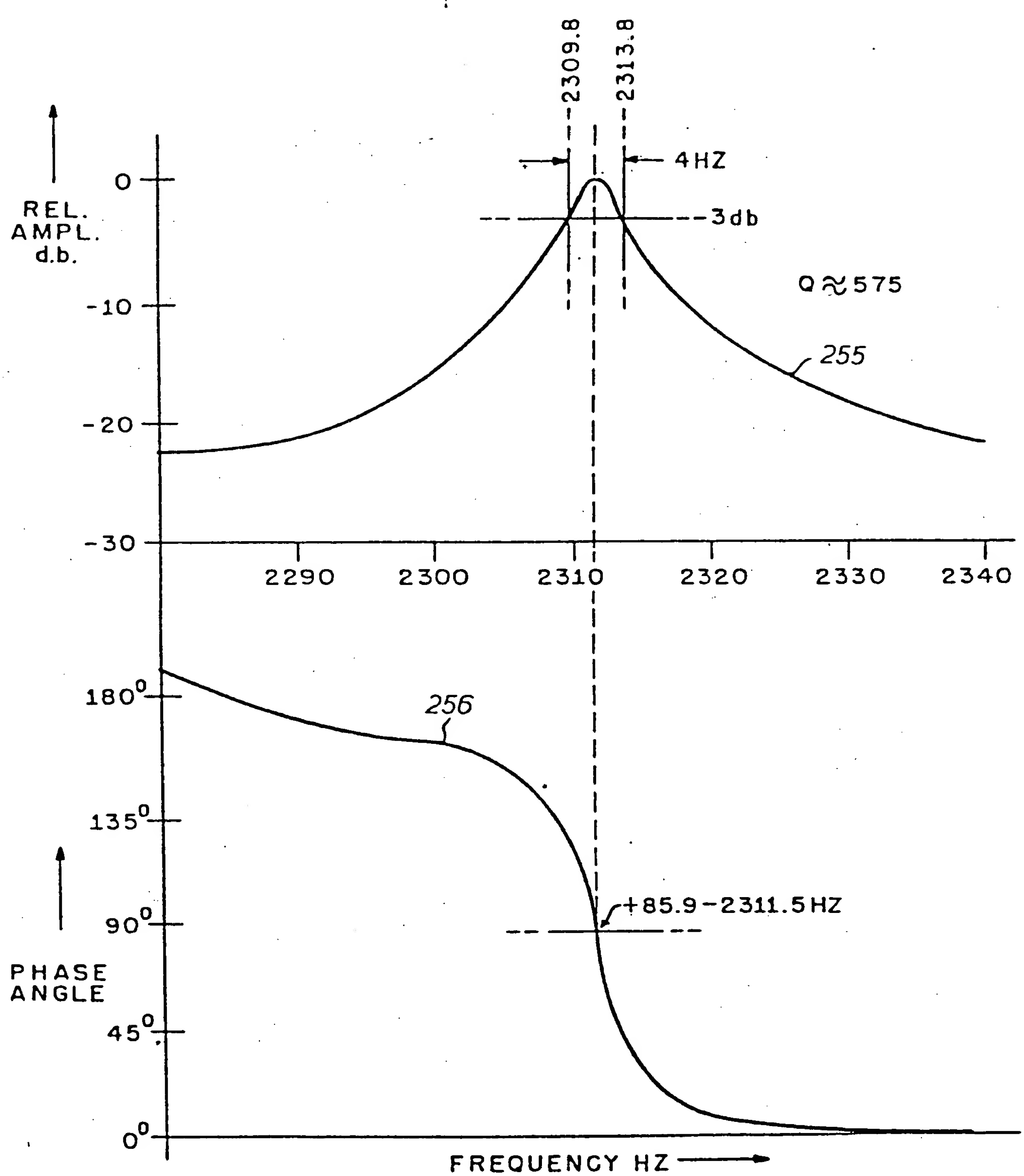

66a
66b
100
109
110
111
S
S
S
PWR AMPL.
101
MODUL.
OSC.
102
112
106
PROGR-AMMER
104
105
D.C. SUPPLY
107
CLOCK
103
108

FIG. 8.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2313.8
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-10
255
-20
-30
2290
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FREQUENCY HZ

FIG.9.

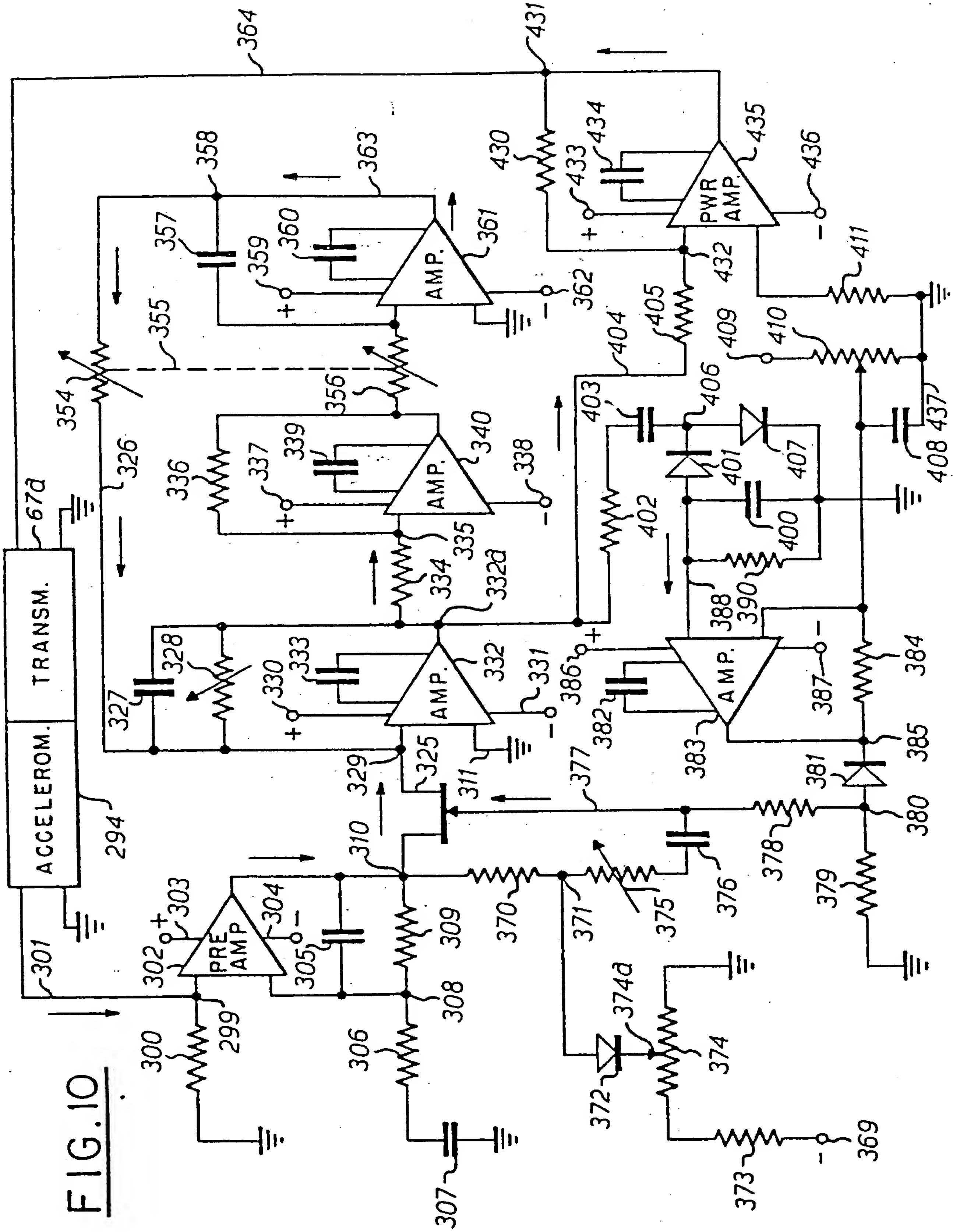
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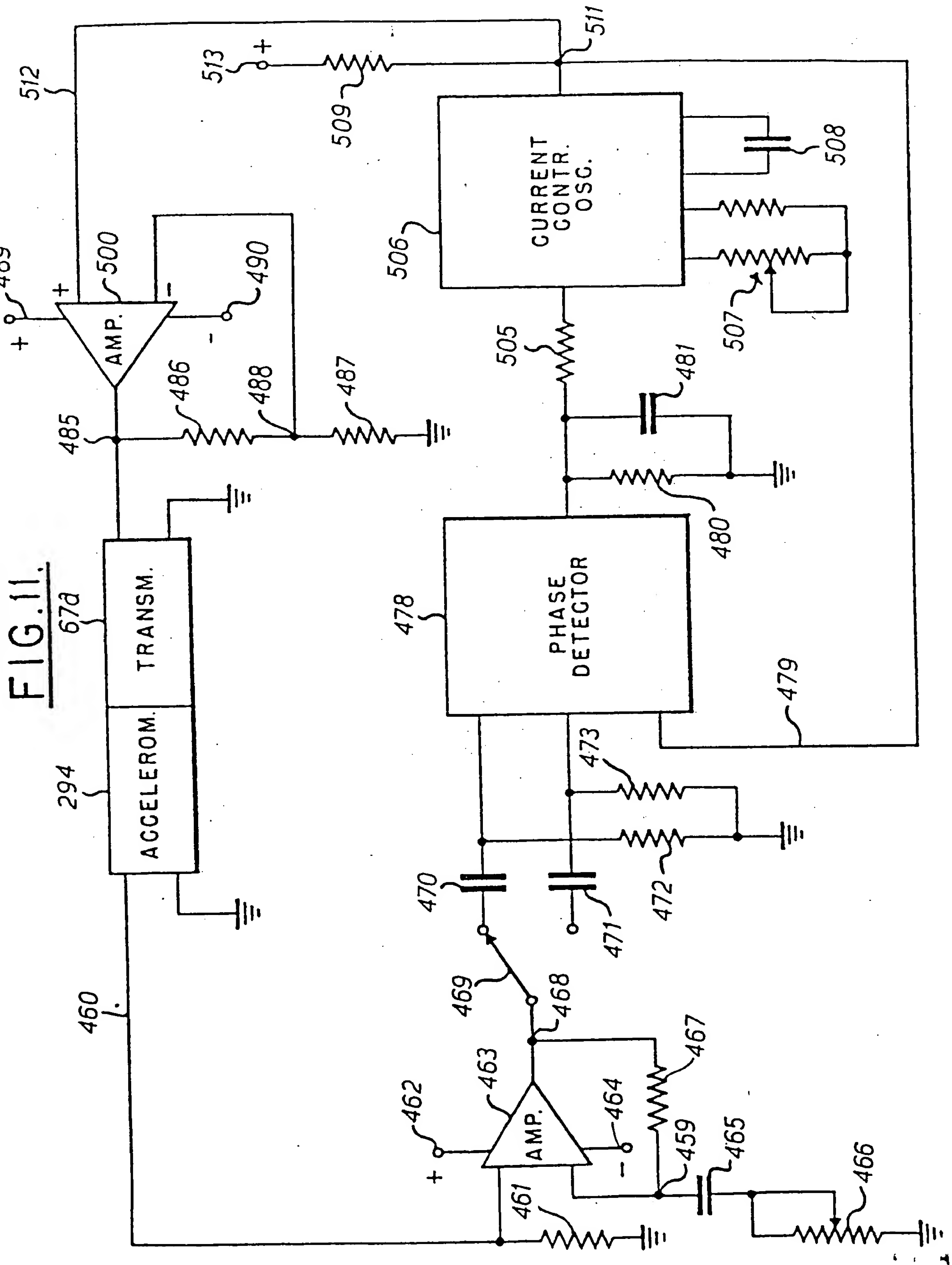
FIG. 10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ACCELEROM.
AMP.
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FIG.11.

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European Patent Office

EUROPEAN SEARCH REPORT

Application number
EP 81300068.4

DOCUMENTS CONSIDERED TO BE RELEVANT			CLASSIFICATION OF THE APPLICATION (Int. Cl.³)
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	
	US - A - 4 139 836 (CHANEY) + Abstract; column 5, lines 17-49; fig. 1,2 + --	1,2,6, 9,12	G 08 C 23/00 G 01 V 3/34 E 21 B 47/12
D	US - A - 4 066 995 (MATTHEWS) + Abstract; column 2, lines 7-46; fig. 1 + --	1	
D,A	US - A - 3 988 896 (MATTHEWS) --		TECHNICAL FIELDS SEARCHED (Int. Cl.³)
	US - A - 3 930 220 (SHAWHAN) + Abstract; fig. 1,2 + --	1,4,5	G 08 C G 01 V E 21 B
	US - A - 3 845 837 (MC EVERS) + Column 4, lines 21-30; abstract; fig. 1-4 + ----	1,12, 13	

CATEGORY OF CITED DOCUMENTS
X: particularly relevant
A: technological background
O: non-written disclosure
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T: theory or principle underlying the invention
E: conflicting application
D: document cited in the application
L: citation for other reasons

&: member of the same patent family, corresponding document

X The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
VIENNA	22-04-1981	NEGWER

EPO Form 1503.1 06.78